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"Venus and Mars: Peculiarities of the Aeronomy and Space Environment of the Weakly Magnetized Planets Related to Their Solar Wind Interaction"

Principal Investigator: Janet G. Luhmann
Project Period: December 1, 1990 - November 30, 1993

This investigation covered a broad range of work by the Principal Investigator and various collaborations, all focused on the general issue of how planetary atmospheres are affected when there is a direct external flowing plasma interaction. The work included studies of the heating effects of atmospheric ions accelerated by the solar wind and then redeposited (precipitated) into the atmosphere [*Luhmann and Kozyra*, 1991], analyses of the upper atmosphere ionization processes [*Zhang et al.*, 1993], analyses of ionospheric data from both in situ-measurements and radio occultations to determine the effect of the solar wind interaction [*Zhang and Luhmann*, 1992], several collaborations on the analysis of Phobos-2 magnetized field and plasma data [*Luhmann et al.*, 1991; *Breus et al.*, 1991; *Gringauz et al.*, 1993; *Kallio et al.*, 1993], and in particular, comparisons with corresponding Venus data to determine differences between the ionospheric effects of the plasma interaction seen at Venus and Mars [*Dubinin et al.*, 1991], contributions to an effort to construct a global hybrid computer simulation of the solar wind interaction with Mars [*Brecht et al.*, 1993], an analysis of the unmagnetized planet-cometary magnetosphere analogy *Luhmann* [1991], and the publication of a number of review papers on Mars-Venus analogies [*Luhmann and Brace*, 1991; *Luhmann*, 1991; *Luhmann et al.*, 1992; *Luhmann*, 1992; *Luhmann and Bauer*, 1992]. Efforts are now underway to extend some of the same analyses to Titan, the next similar body to be probed in some detail during the Cassini mission.

In general, the results of the work show a remarkable similarity in the solar wind effects observed (and expected!) at Mars and Venus. For example, both have practically the same induced magnetotail structure with ionospheric plasma "tail rays" produced by solar wind scavenging [*Dubinin et al.*, 1991; *Luhmann*, 1993]. Both have similar exospheres and ionization processes that feed solar wind scavenging [*Zhang et al.*, 1993], and thus somewhat similar evolutionary loss scenarios [*Luhmann and Bauer*, 1992]. The major differences seem to arise from the smaller size of Mars, which changes scales in the solar wind interaction, and Mars' greater heliocentric distance and thus weaker ionosphere. This "comparative planetology" approach to the study of Mars data that are limited in some respects, and Venus data that are limited in different respects, helps us to fill in the observational "gaps" and to understand how variables such as planet size (e.g., gravity) and heliocentric distance affect the outcome. They

also give us a good idea of what we should be looking for, in terms of measureables, when we finally probe the Martian ionosphere in detail.

The above grant supported both the publication of the research results summarized above and the participation of the Principal Investigator at AGU DPS, and several foreign meetings (IAGA and COSPAR). No patents or inventions resulted from this effort.

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THE SOLAR WIND INTERACTION WITH VENUS AND MARS: COMETARY ANALOGIES AND CONTRASTS

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Abstract. The weakly magnetized terrestrial planets, Venus and Mars, share some common physical processes with comets because of the "direct" interaction between their atmospheres and the solar wind. However, the importance and outcome of these common processes is generally quite different because of the different system scales and atmospheric properties of these two classes of objects. This paper explores some details of their contrasts and similarities in view of the knowledge that we have obtained from the combination of in-situ data and modeling.

Introduction

"Comparative planetology" is a useful practice in that it often gives us a clearer perspective on the system under study by providing other related data from nature's solar system laboratory of "experiments." In the present case, we are considering the class of bodies for which an intrinsic magnetic field plays no significant role in the solar wind interaction. Both comets and the terrestrial planets, Venus and Mars, share this property. They also share the property of a substantial neutral atmosphere. While the relative scales of these bodies and their atmospheres differ appreciably (Venus and Mars have radii of ~6053 and ~3350 km, respectively, and atmosphere scale heights of 10's to 100's of km, while comets have sizes of a few km and atmospheres that can extend up to millions of km), there are physical processes that occur on both that help us to better understand the other. For example, the process of "mass-loading" of the solar wind by planetary or cometary ions must be governed by common physics. It can even be argued that a terrestrial planet is the limiting case of a very large comet with a very dense, shallow atmosphere. However, before making analogies, it is wise to consider the contrasts and similarities between the two systems as we now know them.

Cometary Plasma Processes
Geophysical Monograph 61

Comparisons

Since most of our observational information on the characteristics of the environments of weakly magnetized planets come from missions to Venus (e.g., see the reviews by Russell and Vaisberg, 1983 and Luhmann, 1986), it is perhaps most appropriate to compare comets with Venus. Mars, which is currently under study thanks to the recent experiments on PHOBOS 2 (cf. special 1989 NATURE issue), will be specifically included in the discussion in cases where we have some information from the limited past observations or models, but one should be aware that our picture of the Mars-solar wind interaction may change somewhat over the next few years. However, we do know without question that both planets present obstacles to the solar wind that are little more than planet size (e.g. see Slavin et al., 1982, Russell et al., 1985).

Figures 1a and b compare cartoons of the solar wind interaction with comets and Venus. The basic features of a bow shock and region of draped interplanetary magnetic field dominate both of these pictures. Major differences include the draping of the interplanetary field upstream of the cometary bow shock, but not upstream of the Venus shock, and the presence of an "impenetrable" obstacle at Venus that has a size comparable to the size of the entire interaction region. The other major difference is scale size, which is emphasized in Figure 1c where both the comet and Venus systems are roughly scaled on a diagram of the terrestrial magnetosphere. These differences in some sense form the basis of the forthcoming, more detailed discussion. The pre-shock field draping at the comet is a result of the extent of the atmosphere and hence the region of mass-loaded solar wind, while the deflection of the solar wind around Venus and resulting field draping occurs primarily by virtue of the presence of an ionosphere with sufficient thermal pressure to balance the incident solar wind dynamic pressure. The scale size contrast is a result of the low gravity and high neutral gas production rate at the comet compared to Venus. It will be seen that this scale size difference also has other consequences, such as the

Solar Wind Effects on Atmosphere Evolution At Venus and Mars

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The weak intrinsic magnetism of Venus and Mars leaves these planets subject to some unique atmospheric loss processes. In this paper we briefly review the ways in which material seems to be removed by the solar wind interaction, including atmospheric ion pickup by the solar wind, bulk removal and outflow of ionospheric plasma, and atmospheric sputtering by pickup ions. We then consider the factors in the planets' and sun's histories, such as planetary magnetism, solar luminosity, and past solar wind properties, that must ultimately be folded into considerations of the effects of the solar wind interaction on atmosphere evolution.

INTRODUCTION

The atmospheres of the weakly magnetized planets, Venus and Mars, are subject to some special loss mechanisms because of their direct interaction with the solar wind. This matter arises in a number of papers in the present volume, perhaps because it is a feature that sets these terrestrial planets apart from the Earth, where the atmosphere is "shielded" from the solar wind's direct influences by the geomagnetic dipole field. A brief perspective on solar wind-related effects in the context of all atmospheric loss processes, including Jeans escape and "non-thermal" photochemical mechanisms, can be found in the accompanying paper by Hunten. Details concerning the experimental evidence are reviewed by Moore and McComas (for Venus), and by both Vaisberg and Zakharov (for Mars). As a complement to these, the present discussion is restricted to describing the various mechanisms by which the solar wind is expected to remove atmospheric material. In particular, we consider the "single particle" mechanisms of planetary ion pickup by the electric field associated with the flowing solar wind plasma, and the "fluid" mechanisms which may occur at lower altitudes where the planetary ion density is high. We also consider potentially important secondary effects, such as sputtering of neutral particles, and the factors that may have changed the importance of solar wind-related loss processes over cosmogonical time scales.

Venus and Mars: Atmospheres, Ionospheres, and Solar Wind Interactions
Geophysical Monograph 66

LOSS PROCESSES

Even before the first major space explorations of Venus and Mars provided by the Venera and Pioneer Venus Orbiter (PVO) missions to Venus, and the Viking, MARS, and PHOBOS missions to Mars, it was appreciated that the apparent weakness of their planetary magnetic fields (inferred from earlier Mariner spacecraft flybys) would have consequences for atmosphere escape. Michel [1971] and Wallis [1972], both recognized that planetary ions produced in the rarefied upper atmosphere, where the solar wind plasma penetrated, could be swept away since they would become coupled to that plasma as will be described below.

A rough upper limit to the amount of mass removal that can be accomplished by the solar wind, regardless of the mechanism, can be deduced from momentum conservation considerations. (Our approach here is somewhat different from that of Michel [1971] who based his calculations on a model in which a fraction of the solar wind is deflected around the

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COMPARATIVE STUDIES OF THE SOLAR WIND INTERATION WITH WEAKLY MAGNETIZED PLANETS

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ABSTRACT

The data from the PHOBOS-2 mission has triggered renewed interest in the comparative analysis of plasma and field observations at Mars and similar observations from its practically nonmagnetic sister, the planet Venus. Many of these comparative analysis continue to address the still unresolved question of the strength of the weak intrinsic field of Mars, since differences between the Mars and Venus solar wind interactions are considered to possibly signify the relative importance of the Martian field. In this paper, observations of selected features, including the bow shocks, magnetosheaths, magnetotails, ion environments, and ionospheres, are compared for cases where similar data are available. It is concluded that the observations, as a whole, indicate that there is a great deal of similarity between the two obstacles to the solar wind.

INTRODUCTION

The plasma and field measurements obtained at Mars in 1989, by the PHOBOS-2 spacecraft, sparked a renewed interest in the physics of the interaction of the solar wind with weakly magnetized planetary bodies. In particular, PHOBOS-2 provided the first data on the particles and fields in the deep wake of Mars which were crucial for the assessment of the importance of the Martian intrinsic magnetic field. Given this new information, it is useful to compare both new and old complementary observational results from Mars and Venus, with the aim of reassessing the similarities and differences between their solar wind interactions.

SUMMARY OF OBSERVATIONS

Spacecraft which have contributed to our knowledge of near-Mars space include Mariners 4, 6, 7, and 9, Mars-2, -3, -5, Vikings 1 and 2, and PHOBOS-2. Near-Venus space has been probed by Mariners 2 and 5, Veneras 4, 6, 9, and 10, and the Pioneer Venus Orbiter.

Mariners 4, 6, 7, and 9 provided the first information about the position of the Martian bow shock /1/, radio occultation measurements of the Martian ionosphere /2,3,4,5/, and ultraviolet airglow data that could be used to study the Martian upper atmosphere composition and density /6/. To this, Mars-2, -3, and -5 added measurements within the magnetosheath which suggested the presence of a heavy (probably planetary) ion component in the near-planet plasma, and a Martian "magnetotail" /7/. The Viking 1 and 2 landers gave us the first in-situ measurements of the atmosphere and ionosphere composition and pressure /8,9,10/. PHOBOS-2 was the first spacecraft to probe the deep wake of the planet. Experiments designed to measure the mass and energy of planetary ions detected copious fluxes of escaping oxygen and heavier ions within the inner magnetosheath and wake /11,12/. The magnetometer detected a magnetotail that resembles that of Venus /13/.

At Venus, Venera 4 first encountered the similarly close-in bow shock, while Mariner 5 remotely sensed an unambiguous signature of an "ionopause" in ionospheric electron density profiles obtained by radio occultation experiments. Magnetometers on Veneras 9 and 10 detected a clear signature of an "induced" magnetic tail, produced from draped interplanetary magnetic field, behind the obstacle to the solar wind /2,14/. An extensive period of in-situ measurements by the Pioneer Venus Orbiter (PVO) revealed: a bow shock whose size depends on the solar activity cycle /15/, details of the properties of the "induced" magnetotail /16,17,18/, planetary ions that are in the process of being removed by the solar wind /19,20/, and in-situ measurements of atmospheric and ionospheric properties (see the PVO issue of the Journal of Geophysical Research (December, 1980), the book Venus, edited by L. Colin et al. /14/, and the references in the review by Luhmann /21/).

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Comparisons of Peak Ionosphere Pressures at Mars and Venus with Incident Solar Wind Dynamic Pressure

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Previous calculations of the potential for pressure balance between the solar wind and the ionospheres of the weakly magnetized planets, Mars and Venus, indicated that the maximum or peak ionospheric thermal pressure is sufficient to stand off the solar wind at Venus but not at Mars. In this study we used radio occultation measurements of electron density profiles from Mariner 6 and 7, the Mariner 9 extended mission, and the U.S. Viking orbiters, together with model ion and electron temperature profiles, to derive thermal pressure profiles in the Mars ionosphere. Similarly, Pioneer Venus Orbiter (PVO) radio occultation data and temperature models were used to obtain ionospheric pressure profiles at Venus. Because the radio occultation data give information for both active and quiet phases of the solar cycle, this method allows one to consider how the balance changes between solar minimum and maximum. The comparison of the Mars peak ionosphere pressures with the incident solar wind dynamic pressure suggests that at solar maximum the Mars ionosphere, like that of Venus, should generally be sufficient to balance the incident solar wind pressure. At solar minimum, when the ionosphere is weakest and the solar wind dynamic pressure is highest, only the peak pressures at high solar zenith angles (SZAs) at Mars appear to be strong enough to balance the incident solar wind pressure. This is similar to the situation at Venus at solar minimum. However, due to the lack of radio occultation data for Mars for SZAs less than 45°, we can only infer what happens near the subsolar point. Nevertheless, our results are somewhat contrary to the frequent assumption that the Mars ionosphere is everywhere and always too weak to withstand the incident solar wind dynamic pressure. When one takes into account the SZA dependence of both the incident solar wind pressure and the peak electron density, and the solar cycle variation of the ionosphere, the situations at Mars and Venus appear to be quite similar. Our previous perceptions for Mars may have been colored by the fact that most of the available Mars ionospheric data are from low or moderate solar activity levels.

INTRODUCTION

Different types of interaction between the solar wind and a planet occur, depending on whether the planet has an intrinsic magnetic field or not. For a magnetic planet (e.g., Earth) the shape of the obstacle to the solar wind is determined by the intrinsic field [cf. *Fairfield*, 1971]. Generally, the magnetosphere is far away from the planet, so that no direct interaction between the solar wind and the neutral atmosphere or ionosphere is possible (except perhaps in the cusps).

If a planet has no or only a weak intrinsic field (e.g., Venus) the ionosphere can act as an obstacle to the solar wind. In this case, the obstacle size and shape are determined by the location of the "ionopause", where the incident solar wind pressure is balanced by the ionospheric plasma pressure [cf. *Phillips et al.*, 1988 and references therein]. For a nonmagnetic planet, the solar wind also interacts directly with the neutral atmosphere above the ionopause. *Michel* [1971] describes three types of solar wind interaction with an unmagnetized planet: one in which a magnetic field is induced in the ionosphere which is strong enough to stand off the solar wind; one in which the ionospheric thermal pressure is by itself strong enough to balance the solar wind pressure; and one in which there is direct penetration of the solar wind into the planetary atmosphere analogous to a cometary interaction.

From spacecraft observations it is known that any intrinsic magnetic field at Mars must be small, and it is still a question of controversy as to whether Mars has an intrinsic magnetic field that is strong enough to protect the ionosphere from a direct interaction with the solar wind (for example, see the review by *Luhmann et al.* [1991]). Earlier studies of the pressure balance between the ionosphere of Mars and the solar wind [e.g., *Intriligator and Smith*, 1979] suggested that the Mars peak ionosphere pressure derived from the Viking lander in situ measurements was not sufficient to balance the local solar wind dynamic pressure. On the other hand, the many in situ measurements of ionospheric pressures at Venus at solar maximum by the Pioneer Venus Orbiter (PVO) showed that the Venus ionosphere was robust enough to provide an obstacle most of the time (for example, see *Luhmann* [1986] for a review of the PVO observations). These results suggested that the pressure balance situation at Mars is different from that at Venus. However, the pressure balance calculations for Mars were done only with the two Viking lander in situ density profiles obtained near solar minimum when the ionosphere is expected to be weakest.

In this analysis of the pressure balance question, we use radio occultation measurements of electron density profiles for the ionospheres of both Mars and Venus, together with models of the plasma temperatures, to examine pressure balance over a much larger range of conditions. Because these

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Comparison of Observed Plasma and Magnetic Field Structures in the Wakes of Mars and Venus

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Plasma and magnetic field observations from the Phobos 2 spacecraft at Mars and the Pioneer Venus orbiter (PVO) at Venus show that there are some notable similarities in the structure of the low-altitude magnetotails at both of these weakly magnetized planets. In particular, it is found that when conditions in the interplanetary medium are steady and the orbit sampling geometry is appropriate, two magnetic tail lobes, with an intervening "plasma sheet" or "central tail ray" in the approximate location of the dividing current sheet, are present. This behavior is seen in both the Phobos 2 ASPERA plasma analyzer data and in the PVO Langmuir probe data. In the Phobos 2 data, the tail ray is found to be composed primarily of antisunward streaming oxygen (O^+) plasma which has a bulk velocity consistent with an energy close to that of the upstream solar wind plasma. The PVO Langmuir probe experiment also detected two (or more) additional cold plasma structures flanking the central feature; Phobos 2 data, on the other hand, show a proton plasma "boundary layer" flanking the central (mostly O^+) tail ray or plasma sheet, with sporadic fluxes or rays of O^+ ions. If the latter considered is to be the magnetosheath (solar wind plasma) at the tail boundary, it is mainly the common central tail O^+ features that suggest that there are common planetary ion acceleration and magnetotail formation processes at work in the low-altitude wakes of Mars and Venus. On the other hand, an important contribution from picked-up exospheric hydrogen in the wake at Mars cannot be ruled out.

INTRODUCTION

Until Phobos 2 arrived at Mars in 1989, the only detailed view of the region where the magnetotail of a weakly magnetized planet is formed came from the Pioneer Venus orbiter (PVO) spacecraft. PVO was equipped with instrumentation for making both aeronomical and plasma physical measurements [see *Colin* 1980]. The PVO data of most value for studying the "roots" of the Venus magnetotail were obtained during the extended mission, when the orbit periapsis was allowed to rise from ~150 km altitude to ~2300 km altitude (about 1.3 R_V from the center of Venus). For these orbits, the magnetometer and Langmuir probe (electron temperature probe) experiments provided the most continuous and directly interpretable data. (The PVO plasma analyzer had only ~ 9 min temporal resolution, operated in a variety of modes, and was frequently turned off at periapsis.) Together, the magnetic and plasma electron measurements hinted at the complicated nature of this region [*Brace et al.*, 1987].

Experiments on Phobos 2 have now provided observations behind Mars at ~2.7-2.9 R_M. The complement of plasma instruments on Phobos 2 was different than that on PVO, with greater emphasis on energetic plasma composition measurements [cf. *Lundin et al.*, 1989; *Rosenbauer et al.*, 1989]. Here we examine selected samples from the Phobos 2 data obtained by the ASPERA (automatic space plasma experiment with a rotating analyzer) [*Lundin et al.*, 1989] and MAGMA (magnetic fields near Mars) magnetometer experiments [*Riedler et al.*, 1989], and we consider the parallels that exist between the features seen at Mars and those seen with the Pioneer Venus Langmuir probe and magnetometer experiments at 1.3 R_V behind Venus [*Brace et al.*, 1987]. Comparisons with the Phobos 2 Langmuir probe data, and between the Mars and Venus plasma wave data in these regions, will be described elsewhere by other authors.

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DESCRIPTION OF THE DATA

For the purpose of the present analysis, we selected a subset of the available wake passes, some of which were used by *Luhmann et al.* [this issue] to demonstrate the similarity between the Mars and Venus induced magnetotails. These data were generally chosen because of their clear bipolar signatures in the x (planet-Sun axis) component of the magnetic field. The appearance of this signature requires both a fairly steady interplanetary field orientation and an appreciable angle between the plane of the spacecraft trajectory (an almost polar orbit, in the case of PVO; a more nearly equatorial orbit for Phobos 2) and the plane of the current sheet dividing the induced tail lobes. It was considered that if the plasma behavior in the wake was related to that of the magnetic field, the relationship should be apparent in these particular passes.

As mentioned above, the PVO data used here were obtained with the magnetometer and Langmuir probe experiments during the extended mission. Although higher temporal resolution is available, sufficient detail was obtained by examining 15-s magnetic field averages within ±1 hour of periapsis, and the corresponding 12-s resolution electron density and temperature data from the Langmuir probe. It is assumed that the Langmuir probe is measuring the electrons associated with the "cold" ionospheric plasma, which is primarily O^+ and H^+. Only data obtained in the optical shadow of Venus were used because the Langmuir probe can best measure low densities in darkness (the "noise" level from spacecraft photoelectrons

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THE SOLAR WIND INTERACTION WITH MARS: CONSIDERATION OF PHOBOS 2 MISSION OBSERVATIONS OF AN ION COMPOSITION BOUNDARY ON THE DAYSIDE

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Abstract. This paper describes the features of the boundary in the plasma ion composition near Mars which separates the region dominated by the solar wind protons from the plasma of planetary origin. This boundary was detected by the ASPERA experiment on Phobos 2. It is argued that the features of this boundary seem to be similar to those of other composition boundaries detected elsewhere: the cometopause near comet Halley, and a boundary in the ion composition which appears near Venus during periods of high solar wind dynamic pressure. Numerical modeling of the solar wind interaction with Mars supports the idea that during solar maximum the interaction of the Martian neutral atmosphere with the solar wind can result in a composition transition from solar wind to planetary ions in the low-altitude magnetosheath. This transition occurs because of charge exchange of solar wind protons with the neutral atmosphere and photoionization.

1. Introduction

The detached bow shock first observed near Mars with experiments aboard the spacecraft Mariner 4 (1964), Mars 2 and 3 (1972), and Mars 5 (1974) indicates that near the planet there is an obstacle to the solar wind flow [e.g., Slavin and Holzer, 1982]. The Mars 2 and 3 experiments made it possible to measure dayside crossings of a boundary behind the shock front near the planet (at altitudes slightly above 1000 km) which is identified as an obstacle boundary. The obstacle boundary is a surface where the incoming solar wind flow terminates due to pressure balance between the incident solar wind pressure and the pressure of the ionospheric plasma or intrinsic magnetic field. The analysis of magnetic and plasma measurements near Mars, together with the comparison with the properties of the dayside magnetosphere and magnetotail of the Earth's magnetosphere, led to an early conclusion that the pressure balance at the obstacle near Mars was maintained by the pressure of an intrinsic magnetic field [Dolginov et al., 1973; Gringauz et al., 1973, 1974]. However, these experiments made it impossible to determine unambiguously the magnitude and orientation of the magnetic moment of an intrinsic Martian dipole, because the spacecraft did not penetrate deep into the obstacle boundary on either the dayside or the nightside [e.g., Slavin and Holzer, 1982; Smirnov and Israelevich, 1984].

The poor statistics in the number of crossings of the obstacle boundary led to uncertainty in its shape and, in particular, in its altitude at the subsolar point. The latter is important for estimating the contribution of the Martian upper atmosphere to the interaction process. Attempts were made to determine these obstacle characteristics using the comparison of the experimentally determined position of the shock with the position of bow shocks for obstacles of different shapes and sizes calculated from hydrodynamic models [Bogdanov and Vaisberg, 1975; Dolginov, 1978; Slavin et al., 1983]. These estimates led to significantly different estimates of the altitude of the obstacle nose (about 400 to 700 km in the paper by Bogdanov and Vaisberg [1975], about 510 km + 20% in the paper by Slavin et al. [1983], and about 600 to 900 km in the paper by Dolginov [1978]), using the same hydrodynamic model [Spreiter and Rizzi, 1972; Spreiter and Stahara, 1980 a, b] and the same experimental data.

Thus, using the results of "pre-Phobos" missions which were carried out during the declining phase of solar activity and near solar minimum, the usual conclusion was that the obstacle boundary at Mars is a magnetopause. However, details such as the properties of the plasma in the vicinity of the obstacle boundary, and the contribution of the induced and intrinsic magnetic field to the obstacle formation, were still subjects of discussion. The Phobos 2 mission has again generated interest in the nature of the solar wind obstacle near Mars, which is not completely resolved in spite of the new observations.

2. ASPERA and MAGMA Experiments on Board the Phobos 2 Spacecraft

As illustrated by Figure 1, the elliptical "transfer" orbit of Phobos 2 provided three crossings of the shock front in the subsolar

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A COMPARISON OF INDUCED MAGNETOTAILS OF PLANETARY BODIES: VENUS, MARS, AND TITAN

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Abstract. The Pioneer Venus orbiter (PVO), PHOBOS 2, and Voyager 1 spacecraft have together provided observations of three planetary bodies with induced magnetotails: Venus, Mars, and Titan. During the extended mission of PVO, the tail of Venus was probed at an altitude of ~1.3 planetary radii, which provided a more appropriate basis for comparison with the Mars data (at ~2.7 planetary radii), and Titan data (~2.5 planetary radii downstream), than the previously analyzed Venus tail data obtained near PVO apoapsis (~12 planetary radii). A parallel examination of the magnetic properties of these tails at downstream distances within 3 planetary radii reveals the following similarities and differences. In the cases of Venus and Mars, which are always embedded in the supermagnetosonic solar wind flow, the tail lobe fields are smoothly joined to the draped magnetosheath fields at their outer boundaries, but separated in the center by a distinct, and sometimes narrow, current sheet. The tail of Mars has a cross section that is wider, when scaled by the planet radius, than that at Venus (as found by earlier MARS spacecraft experiments), a lobe field strength that is about the same as that at Venus in spite of the factor of ~3 smaller interplanetary field at Mars, and a cross-tail field strength that exceeds that at Venus by ~1.5 times. The tail of Titan appears similar to the others except that there is no bow shock and little or no draped magnetosheath field signature since the surrounding magnetospheric plasma flow is submagnetosonic (although super-Alfvenic). The lobe field strengths are about half those at Venus and Mars, while the cross-tail field is almost negligible. The near-Titan tail diameter is close to the body diameter. In place of the smooth transition to a draped magnetosheath field at the tail boundaries, as seen at Venus and Mars, the Titan observations show current sheets where the field rotates to its external orientation. It is shown that the Titan wake magnetic signature can be simulated with a model field composed of a cylindrical boundary containing antiparallel axial "tail lobe" fields, surrounded by a field described by streamlines of incompressible flow around a cylinder. Simulation of the magnetic fields observed at Mars and Venus, on the other hand, requires a draped magnetosheath field model with an appropriately oriented comet-tail-like model in its interior.

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Introduction

Planetary bodies without intrinsic magnetic fields, but with substantial atmospheres, are known to possess cometlike "induced" magnetotails as a result of the atmospheric mass loading and subsequent "draping" of passing flux tubes. The properties of these induced magnetotails depend on the characteristics of both the incident flowing magnetized plasma and the atmosphere and on the atmospheric ionization processes. In general, induced planetary magnetotails should have lobe polarities that are controlled by the orientation of the magnetic field in the surrounding flow as is observed in a comet tail [cf. Smith et al., 1986; Schwingenschuh et al., 1987; McComas et al., 1987], and lobe strengths that depend on the amount of mass loading [cf. Russell et al., 1989].

The Pioneer Venus orbiter (PVO) made the first in situ observations of an induced planetary magnetotail behind Venus [Russell et al., 1981; Russell, 1986]. Shortly thereafter, Voyager 1 flew through the wake of Titan, where a similar magnetic structure was detected [Ness et al., 1982]. Most recently, the spacecraft PHOBOS 2 finally probed the magnetic field in the deep Martian wake [Riedler et al, 1989]. The more than 4000-orbit mission of PVO provided many dozens of both near (inside ~1.3 Venus radii ($R_V \approx 6053$ km)) and far (~10-12 R_V) wake crossings for study. Several papers describing the magnetic properties of the distant Venus tail [Russell et al., 1981; Saunders and Russell, 1986; McComas et al., 1986; Moore et al., 1990], including its comparison to a comet tail [McComas et al., 1987], have been published, but little discussion of the more recently obtained low-altitude tail data has appeared. The Voyager 1 data from Titan, while consisting of only a single flyby at a distance of ~2.5 Titan radii ($R_T \approx 2575$ km), provided an important first look at the wake of a planetary satellite with a significant atmosphere. These Titan observations immediately inspired analogies with Venus [Ness et al., 1982; Kivelson and Russell, 1983; Verigin et al., 1984].

Now that several tens of examples of Martian magnetotail data in the orbit of Phobos (located at ~2.7 Mars radii ($R_M \approx 3390$ km)) are available from the PHOBOS 2 mission [see Yeroshenko et al.,

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DAYSIDE PICKUP OXYGEN ION PRECIPITATION AT VENUS AND MARS: SPATIAL DISTRIBUTIONS, ENERGY DEPOSITION AND CONSEQUENCES

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Abstract. The fluxes and energy spectra of picked-up planetary O^+ ions incident on the dayside atmospheres of Venus and Mars are calculated using the neutral exosphere models of Nagy and Cravens (1988) and the Spreiter and Stahara (1980) gasdynamic model of the magnetosheath electric and magnetic field. Cold (~10 eV) O^+ ions are launched from hemispherical grids of starting points covering the daysides of the planets and their trajectories are followed until they either impact the dayside "obstacle" or cross the terminator plane. The impacting, or precipitating, ion fluxes are weighted according to the altitude of the hemispherical starting point grid in a manner consistent with the exosphere density models and the local photoion production rate. Maps of precipitating ion number flux and energy flux show the asymmetrical distribution of dayside energy deposition expected from this source which is unique to the weakly magnetized planets. Although the associated heating of the atmosphere and ionosphere is found to be negligible compared to that from the usual sources, backscattered or sputtered neutral oxygen atoms are produced at energies exceeding that needed for escape from the gravitational fields of both planets. These neutral "winds," driven by pickup ion precipitation, represent a possibly significant loss of atmospheric constituents over the age of the solar system.

1. Introduction

The atmospheres of the weakly magnetized planets Venus and Mars are subject to some unique energization and loss processes because of their direct exposure to the solar wind. Present observational evidence for the existence of such processes consists principally of anomalous ionosphere plasma density profiles and temperatures at both planets (cf. reviews by Luhmann [1986] and Barth et al. [1990]), although other puzzles such as the lack of substantial amounts of water are not without a possible connection to the solar wind interaction [e.g., McElroy et al., 1977, 1982].

The solar wind is generally considered to have two possibly significant effects on the atmospheres of Venus and Mars. One is the heating of the ionospheres, and perhaps the neutral atmospheres. The other is the scavenging or loss of planetary ions which get caught up in the solar wind flow.

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The former effect has been examined at some length using models. The basic problem is that models which start with the observed neutral atmospheres exposed only to the properly scaled solar radiation fluxes do not reproduce the observed ion and electron temperature profiles [cf. Cravens et al., 1980; Chen et al., 1978]. To obtain the observed profiles, the models have to include both horizontal magnetic fields (of either induced or intrinsic origin) to limit heat conduction, and heat sources at their upper boundaries. These extra heat sources have generally been attributed to the solar wind, although the mechanisms for such heating are not well understood. For example, Taylor et al. [1979] considered the possibility that Landau damping of the plasma waves (of unknown origin) observed at the ionopause of Venus could heat the electrons there. Perez-de-Tejada [1987] has repeatedly argued that some type of viscous interaction in the velocity shear layer at the ionopause causes heating at both Venus and Mars. The planetary ion losses resulting from scavenging processes are more definitely attributable to the solar wind.

The mere existence of a well-defined ionopause at Venus [cf. Brace et al., 1980] testifies to the ability of the solar wind to remove planetary ions. Moreover, observations of oxygen ions near Venus by the plasma analyzer on the Pioneer Venus Orbiter have shown that the picture of ion scavenging illustrated in Figure 1, wherein the planetary ions created in the atmosphere above the ionopause are accelerated by the convection electric field of the solar wind, explains where the planetary ions are detected in the magnetosheath and tail. Phillips et al. [1987], Slavin et al. [1989] and Intriligator [1989] have all found asymmetries in the spatial distributions of energetic O^+ "pickup" ions which confirm the operation of this process. The asymmetry is essentially a finite gyroradius effect which assumes importance because the planet size is comparable to or smaller than the gyroradii of the dominant exospheric oxygen ions [cf. Wallis, 1972; Cloutier et al., 1974; Wallis, 1982]. Because of their large gyroradii, some of the picked-up particles reenter the atmosphere while the others are carried away by the solar wind. Other observations of plasma "clouds" or "rays" at Venus suggest the action of an additional "bulk" removal of ionospheric plasma at the planetary ionopause [cf. Brace et al., 1982; Russell et al., 1982], but this second mechanism is more difficult to evaluate and so is not considered here. The recent PHOBOS spacecraft observations of oxygen ions flowing away from Mars [cf. Lundin et al., 1990] may similarly fit this picture, but the required analyses have not yet been completed. The

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A Model of the Ionospheric Tail Rays of Venus

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Distinctive structural patterns in the "tail rays" that form the outermost reaches of the Venus nightside ionosphere were observed on the Pioneer Venus Orbiter. The measurements further suggested that the tail rays are the vehicle for significant escape of atmospheric oxygen, but the manner in which they fit into the scenario of solar wind scavenging and the physics behind their formation remain unexplained. In this paper a model of tail ray generation and morphology is proposed which is based on knowledge of the magnetic field structure in the low-altitude magnetosheath and near-wake, where the tail rays are observed. The model applies specifically to those regions where the plasma pressure in the tail rays is less than the field pressure. It is shown that many of the observed structural patterns can be explained if it is assumed that initially low energy ionospheric O^+ ions are picked up by an externally imposed convection electric field from a thin source region around the terminator. Gravity is found to play a significant role in determining the ion trajectories and hence the modeled tail ray structures. The model can produce single, double, triple, or quadruple thin tail rays, all of which are observed. The energies of the particles are also consistent with the available data. The reported tail ray dependence on solar EUV flux and solar wind dynamic pressure naturally fits into the proposed concept. The implication for ion escape is that no special mechanisms are required to explain Venus tail rays. They may be simply interpreted as the low-altitude, low-energy manifestation of the standard ion pickup process at a weakly magnetized planet.

INTRODUCTION

Pioneer Venus Orbiter (PVO) observations revealed that the top of Venus's nightside ionosphere is highly structured [e.g., *Brace et al.*, 1987]. The appearance of the time series of the Langmuir probe electron density measurements, showing one or more sharply defined density maxima along wake passes in the altitude range from ~1500 km to ~2300 km, inspired the adoption of the cometary term "tail rays." Using data from several other PVO instruments, *Brace et al.* [1987] studied the details of the Venus tail rays observed on the first few nightside periapsis traversals and deduced that they were composed of escaping superthermal ionospheric O^+ ions. They did not attempt to formulate a physical scenario for the escape. However, they did estimate from the observations that the escape flux could be on the order of 10^{25}-10^{27} O^+ ions/s, which is significant compared to oxygen loss from other processes at Venus [e.g., *McElroy and Prather*, 1982].

One question that has remained outstanding and is pertinent to the atmosphere evolution issue is whether the tail rays result from some special physical mechanism other than the familiar ion pickup by the convection electric field in the vicinity of the ionopause. Another mechanism would of course enhance the losses beyond those estimated simply by calculating the expected production of oxygen ions above the ionopause by photoionization, impact ionization, and charge exchange [e.g., *Zhang et al.*, 1993]. There is also the more basic question concerning the reason for the observed structure of the tail rays.

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In this paper a model is used to demonstrate that the basic properties of at least some Venus tail rays can be reproduced by simply mapping low-energy O^+ ions picked up at the terminator magnetosheath/ionosphere boundary into the low-altitude wake. This mapping is done by tracing test particles in a model of the wake magnetic and electric field structure and is therefore appropriate for those structures wherein the plasma pressure is less than the magnetic field pressure (e.g., low plasma beta cases). The field model is based on the magnetic field observed in conjunction with these tail rays together with the expectation that the flow of the low-altitude magnetosheath/ionosphere boundary layer and underlying wake plasma will approach stagnation such as that observed in a cometary magnetotail [e.g., *McComas et al.*, 1987]. The results suggest that the thinness of the terminator source region is responsible for the fine tail ray structures observed in the Venus wake and that no special processes other than simple ion pickup are required to generate these tail rays.

OBSERVED TAIL RAY CHARACTERISTICS

As mentioned above, Venus tail rays were observed on nightside PVO periapsis passes in the altitude range between about 1500 km and 2300 km [*Brace et al.*, 1987]. Figure 1 displays several PVO time series of Langmuir probe and magnetometer data reproduced from *Dubinin et al.* [1991]. These represent the three most frequently observed tail ray structures, i.e., single, double, and triple peaks (Figures 1*a*, 1*b*, and 1*c*, respectively) in the electron density [*Brace et al.*, 1983]. Four tail rays are also occasionally seen, as are complex multirayed structures that do not seem to represent characteristic patterns and thus may signify temporal variation. The underlying magnetic field in the cases of the well-defined

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Oxygen Ionization Rates at Mars and Venus: Relative Contributions of Impact Ionization and Charge Exchange

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Oxygen ion production rates above the ionopauses of Venus and Mars are calculated for photoionization, charge exchange, and solar wind electron impact ionization processes. The latter two require the use of the Spreiter and Stahara (1980) gas dynamic model to estimate magnetosheath velocities, densities, and temperatures. The results indicate that impact ionization is the dominant mechanism for the production of O^+ ions at both Venus and Mars. This finding might explain both the high ion escape rates measured by Phobos 2 and the greater mass loading rate inferred for Venus from the bow shock positions.

INTRODUCTION

The most basic source of ions escaping from Mars and Venus is solar wind pickup of ions produced above the "ionopause". Phobos 2 observations of O^+ ion pickup suggest escape rates at Mars of $\sim 5 \times 10^{24}$ to $\sim 2 \times 10^{25}$ ions/s [*Lundin et al.*, 1990; *Verigin et al.*, 1991]. Mechanisms other than the simple pickup process have been invoked to explain these observations, because calculations indicate that the photoionization rate above the ionopause is less (by approximately on order of magnitude) than the observed escape rate. Similarly, the position of the Venus bow shock is observed to change with the solar cycle and to be located at larger distances than expected from gas dynamic models [e.g., *T.L. Zhang et al.*, 1990]. It has been argued that mass loading of the solar wind plasma by the ions from the hot oxygen corona could push the shock outward [e.g., *Belotserkovskii et al.*, 1987], but *Spreiter and Stahara* [1992] have reported that the results are in error and that mass addition of the amount considered by *Belotserkovskii et al.* [1987] results in insignificant movement of the bow shock. This finding is consistent with the results of an independent and different type of analysis by *Moore et al.* [1991] in which it is shown that the previously estimated mass production (e.g., ion production) rates are too low.

Here we show that if impact ionization and charge exchange are included as ionization mechanisms for the upper atmosphere and expected hot oxygen corona, ion production rates comparable to the loss rates seen on Phobos 2 are obtainable. Moreover, these additional ion production rates contribute substantially to the mass loading rate at Venus. Of the two mechanisms, impact ionization by shock-heated magnetosheath electrons appears to be the more important at both Venus and Mars. The implication is that no mechanism other than solar wind pickup of ions produced above the ionopause is necessary to explain both the measured loss rates of O^+ at Mars and the mass loading effects at Venus. These results also show that in models of the solar wind interaction with the weakly magnetized planets, impact ionization of neutrals is an important factor and should not be ignored.

The calculations are carried out using the oxygen exosphere models of *Nagy and Cravens* [1988] and the gas dynamic magnetosheath model of *Spreiter and Stahara* [1980] which are described below. The former provides a description of the high altitude neutral population, while the latter allows us to compute the charge exchange and electron impact ionization rates using the methods described by *Cravens et al.* [1987] for comets.

OXYGEN EXOSPHERE MODELS

Two stream models [*Nagy and Cravens*, 1988] have been successful in describing the hot oxygen exosphere density profiles observed at Venus. In these models, the main source for hot oxygen (O^*) in the upper atmospheres of Mars and Venus is dissociative recombination of O_2^+:

$$O_2^+ + e \rightarrow O^* + O^*$$

The value of the dissociative recombination coefficient is $\alpha = 1.6 \times 10^{-7} (300/T_e)^{0.55}$ cm^3 s^{-1} [*Mehr and Biondi*, 1969], where T_e is the ionospheric electron temperature in kelvins. Other sources of hot oxygen are charge exchange of hot thermal ionospheric atomic oxygen ions with neutral atomic oxygen and with hydrogen, but these processes are negligible compared to the dissociative recombination source. Since the details of the two-stream modeling technique are described elsewhere, we here simply summarize by saying that the method involves the solution of coupled transport equations for upward and downward fluxes of oxygen atoms at different energies and for a range of altitudes. The upward flux at the exobase is used to calculate the altitude profile of exospheric density using Liouville's theorem (also see M.H G. Zhang et al., The ancient oxygen exosphere of Mars: Implications for

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Three-Dimensional Simulations of the Solar Wind Interaction With Mars

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Three-dimensional hybrid particle simulations of the dayside portion of the Mars/solar wind interaction have been performed. These simulations are compared with the in situ measurements taken during the elliptical orbits of Phobos 2. The comparisons show considerable agreement between the magnetic field data and the simulations results. The results of the simulations bring into question the type of structures created in the subsolar region of Mars. It appears that the large larmor radius of the solar wind ions prevents the formation of a traditional collisionless shock in the subsolar region of the interaction.

1. INTRODUCTION

Renewed interest in the topic of the solar wind interaction with the planet Mars has been generated with the insertion of Phobos 2 into Martian orbit on January 29, 1989. This spacecraft sampled altitudes lower than any of the previous spacecraft (Mariner 4 and Mars 2, 3, and 5) carrying magnetometers. All of these spacecraft detected a shock structure surrounding Mars [cf. *Vaisberg et al.*, 1990]. Based on data returned from the Phobos mission, it is still impossible to determine whether or not Mars has a weak intrinsic magnetic field. However, these data suggest that the Mars shock shape and location behave similar to the Venusian bow shock. Many of these comparisons can be found in the special section on Venus and Mars in the *Journal of Geophysical Research*, (*96*(A7), 11,019–11,290, 1991).

The comparison of the two planets and the debate concerning the existence of an intrinsic magnetic field is largely based on the shock location data. Indeed, one of the main purposes of the Phobos magnetic field investigation [*Riedler et al.*, 1989] was to understand the interaction of the solar wind with Mars. This interaction must be understood before the existing shock location data can be properly interpreted. The purpose of the research presented in this paper is to obtain a better understanding of the solar wind interaction with Mars via numerical simulation.

While the behavior of the shocks found at Mars and Venus demonstrate considerable similarities, there are some interesting differences. For example, *Schwingenschuh et al.* [1990] found that while the subsolar shock location at 1.47 planetary radius ($R_M \sim 3395$ km) is similar to the Venusian subsolar shock location, the flare angle of the Martian shock is greater than that detected at Venus; that is, the terminator shock position is 2.3–2.5 for Venus and 2.7 for Mars. Finally, the magnetic field and plasma observations near the subsolar Martian shock generally appear more variable than the data returned by the Pioneer Venus orbiter (PVO) from Venus. Some of these features are to be expected, but others are not necessarily consistent with the hydrodynamic picture usually used to describe the solar wind interaction with planets such as Mars and Venus.

For example, when the Mach number is increased, the fluid picture [cf. *Van Dyke*, 1982] requires that the shock move inward toward the obstacle and the flare angle of the shock diminish. The solar wind conditions at Mars are generally consistent with a magnetosonic Mach number M_{ms} that is considerably greater than that near Venus. This would imply that the relative standoff distance from the subsolar Martian shock to the surface of the planet should be smaller than measured at Venus; instead, it is about the same relative to the planet radius. Similarly, the larger measured flare angel of the Mars shock is inconsistent with the fluid picture. On the other hand, the existence of more magnetic variability observed by Phobos 2 is consistent with the higher Alfven Mach number M_A. Given these features of the Martian shock data and the limited amount of data returned by the Phobos mission before it ceased to function, many interesting questions remain to be addressed.

In this paper we apply the three-dimensional hybrid particle code HALFSHEL [*Brecht*, 1990; *Brecht and Ferrante*, 1991] to study details of bow shock location, shape, and other attributes for an unmagnetized planetary obstacle of the size of Mars. This numerical approach permits study of the electromagnetic structure associated with the Martian shock. It also allows examination of kinetic behavior such as particle-wave interactions, ion distribution functions, and the role of finite ion gyroradius effects expected to occur when the solar wind ions interact with a Martian size obstacle. Our primary emphasis is on the location and structure of the Martian shock as produced from HALFSHEL simulations. The results of these simulations raise some interesting questions concerning the assumptions made in previous interpretations of the data returned by the Phobos mission.

In the following sections we present the results of the HALFSHEL simulations of Mars where no ionosphere has been added and the planet (modeled as a conducting sphere) is resolved to the terminator line. This clearly represents a simplification of the actual Mars/solar wind interaction, but it provides a fiducial point for future simulations which will possess the additional complexity of the planetary iono-

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31. THE INTRINSIC MAGNETIC FIELD AND SOLAR-WIND INTERACTION OF MARS

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Plasma and field measurements on various spacecraft have demonstrated that Mars has an intrinsic dipole magnetic field that is no more than $\sim 10^{-4}$ *times as strong as that of the Earth. This difference is attributed to the weakness or absence of dynamo activity in the Martian core. An important consequence of the weak intrinsic field is a Venus-like interaction between the solar wind and the atmosphere. It has been found that this interaction leads to losses of Martian atmosphere constituents that are important for the atmosphere's evolution.*

INTRODUCTION

A. Intrinsic Planetary Magnetic Fields

It has been known for over 500 yr that the Earth possesses an intrinsic magnetic field, approximately dipolar, like that of a bar magnet (Gilbert 1600). This field is generated by a dynamo produced by convection in the electrically conducting, rotating, molten core (Gubbins 1974). In the last century astronomers have discovered that the Sun as well as stars in general also